Bioethanol production under endogenous crop prices: Theoretical analysis with an empirical applications to barley

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Abstract— **The European Union's Emission Trading Scheme (EU-ETS) and the current renewable resource program provide strong incentives to use agricultural crops either for combustion in power plants to produce electricity and heat or as a feedstock for transportation fuels. In this paper we examine the social desirability of ethanol production from agricultural crops. To endogenize the competition on land use, we employ a Ricardian model of heterogeneous land quality, where land is allocated to alternative crops on the basis of their relative profitability. The model comprises three land use types: bioenergy crop, conventional feed crop and green set-aside. Industry demands crops for both ethanol and feed production. Effects on the GHG balance are explicitly taken into account in the analysis. Theoretical model characterises both the private and social optima and examines endogenous price effects. Theoretical framework is applied to barley production in Finland. We found that the socially optimal demand for barley is 13.3 % higher than demand obtained in the private optimum. This implies shifts in land allocation, fertilizer intensity and prices. Considering the climate impacts of crop cultivation, the land area devoted to green set-aside greatly increases in the social optimum as compared with the private optimum.**

Keywords— **biofuels, agricultural land allocation, heterogeneous land quality.**

I. INTRODUCTION

The European Union's Emission Trading Scheme (EU-ETS) and the current renewable resource program have changed production incentives in favour of renewable energy production. Their goal is to reduce CO_2 emissions and promote the production and use of bioenergy and biofuels. Emission trading provides favours to use of agricultural bioenergy crops in power plants to produce electricity and heat. One of the goals of the renewable resource use program is to reduce fossil fuel use in transportation. By imposing blending requirements the program has promoted the use of liquid biofuels, such as ethanol and biodiesel, in transportation.

The primary goal of biofuel production is to reduce fossil greenhouse gas (GHG) emissions. Comparative analysis of biofuels and fossil transport fuels requires life cycle assessment (LCA) for the determination of life cycle GHG profiles of different biofuel chains and corresponding life cycle impacts of fossil transport fuels. The main focus of the most LCA studies providing comparative analysis of biofuels and fossil fuels have been on energy and GHG balances of alternative options. These studies have demonstrated that in comparison to gasoline and diesel fuels most biofuel pathways provide GHG emission reductions when compared to fossil fuels. However, GHG emission reductions provided by alternative biofuel chains may vary significantly in different studies. This variation in the results is mainly driven by differences in the treatment of co-products (protein meal from oilseed crops and feed from distiller grains) and how impacts are allocated to them. Also the quantity and type of process energy used (coal, natural gas etc.) has significant impact on the results.

Thus, an analysis of the socially optimal production of bioenergy crops must take into account greenhouse gas balance of the whole life cycle. This is, however, not enough. Promoting bioenergy and biofuel production entails increased competition on agricultural land that was previously allocated to food, feed and fibre production as well as for environmental purposes (such as green set-aside). Even if substituting biofuels for gasoline reduces direct GHGs and thus provides carbon benefits of using that land for biofuels it may be the case that their production involves indirect carbon costs through land use change (the carbon storage and sequestration sacrificed by diverting land from its existing uses) in terms of reduced amount of grasslands and green set-asides [1].

Moreover, cropland diverted from feed and food production in Europe and the U.S. could provide strong incentives for taking additional land into cultivation of feed and food crops in other parts of the world (such as Brazil, China and India). This indirect land use change could lead to very high land-use change related emissions [1].

Ethanol can be produced from barley or wheat under existing cultivation methods. The higher the amount of land allocated outside of food and feed production, the higher one can expect the prices of cereals to be. In the similar vein, increased supply of crops to ethanol production will decrease the return that the farmer can obtain from their cultivation. Examination of social desirability of ethanol production must therefore be rooted in an analysis that endogenizes crop prices. Then, endogenous crop prices allow for the analysis of the trade-off between climate benefits from bioenergy crop production (either for heat and electricity or biofuel) and consumers' valuation of food and feed production.

In this paper we examine the social desirability of ethanol produced from agricultural crops. To endogenize the competition on land use, we employ a Ricardian model of heterogeneous land quality, where land is allocated to alternative crops on the basis of their relative profitability. The model comprises three land use types: bioenergy crop, conventional feed crop and green set-aside. Effects on the GHG balance are explicitly taken into account. To endogenize the bioenergy crop price we assume that industry demands the crop for both ethanol and feed production, and thus, competes on the crop. We apply the theoretical framework to ethanol produced from barley in Finland.

The rest of the paper is organized as follows. In section 2 we develop the theoretical framework and compare the privately and socially optimal solutions. Section 3 builds the parametric version of the model and presents the results. Concluding section 4 ends the paper.

II. ETHANOL PRODUCTION AND COMMODITY MARKETS: A FRAMEWORK AND SOCIAL OPTIMUM

In this section we develop a framework to determine the social optimum for bioenergy crop production. Our framework integrates the LCA aspects to conventional economic analysis. We assume that bioenergy crop is used in the production of both biofuels and animal feed; thus, there is competition for bioenergy crop produced by farmers. By assumption, bioenergy crop is produced under heterogeneous land quality. We define the socially optimal production but also characterize the behavioural functions (supply and demand) to determined the equilibrium price in the empirical application.

A. The framework and the LCA production chain

We use greenhouse gas balance between conventional gasoline and ethanol as an indicator of climate impacts of production in the economy. Following [2], the production chain of ethanol and the CO_2-eq emissions from the chain that we apply in the analysis is presented in Figure 1 (page 3).

Reflecting Figure 1, we first develop the description of climate impacts of production. Let $Q = g(\hat{h}, E)$ be the amount of ethanol produced, where $\hat{h}$ denotes bioenergy crop and E energy used in the production process. The parameter ε denotes the amount of CO_2-eq emissions reduced by the use of ethanol when compared with conventional gasoline (kg CO_2-eq / t ethanol). This parameter value depends on the optimal fertilizer intensity l^{1*} of bioenergy crop, per hectare yield f^{1*} of bioenergy crop and land allocation between crops and green set-aside.

The social valuation function of climate impacts of ethanol production in both ethanol production process and agriculture are:

$$b = b\left[\varepsilon g(\hat{h}, E) - \sum_{i=1}^{3} \mu^i L^i\right] \quad (1)$$

In equation (1), b denotes the value that society places on the reduction of CO_2, which is assumed to be

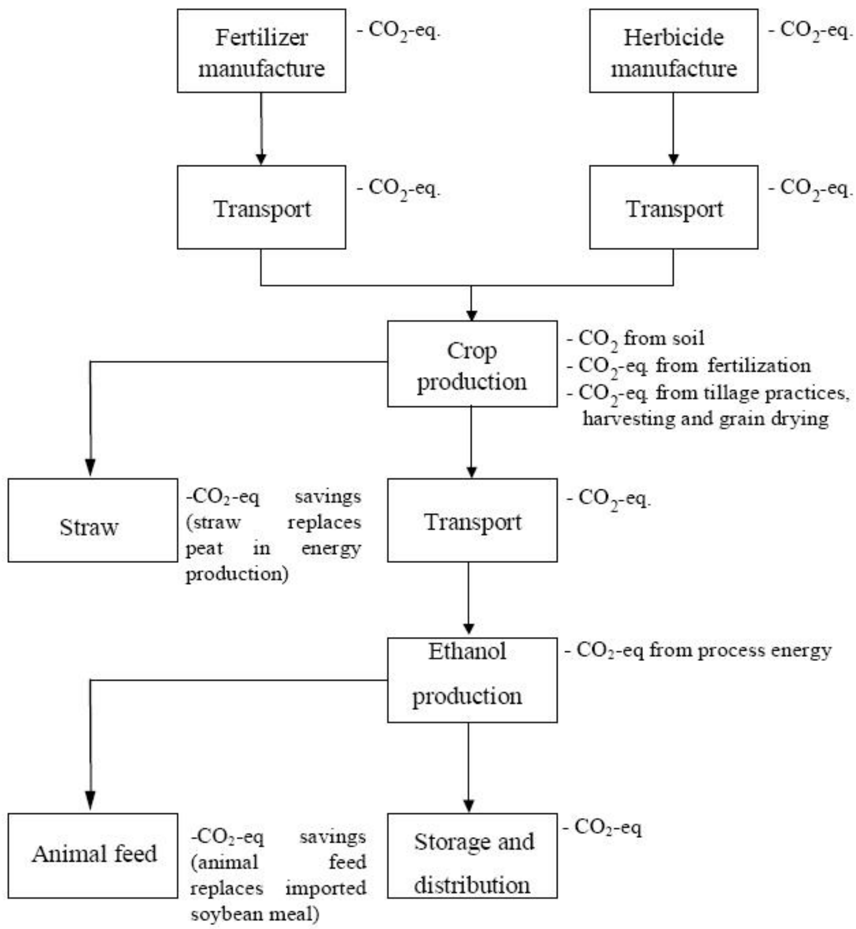

Fig.1 Production chain of ethanol and LCA impact

concave, thus $b' > 0$ and $b'' < 0$. Furthermore, L^i is the land area allocated to the cultivation of crop *i* and parameter μ^i represents CO_2-eq emissions from soil, pesticides production and use, transportation of inputs and outputs and CO_2-eq emissions from agricultural practices (kg CO_2-eq / hectare) for crop *i*.

Turning next to the target functions of market agents, we assume that the ethanol firm manufactures animal feed as a by-product from the residues and denote it by $a(\hat{h})$. Let p^e be the price of ethanol, p^r the price of animal feed, p^1 the price of bioenergy crop and $\tilde{w}$ the price of energy. Then, the profits of the ethanol firm is given by $\pi^e = \left[p^e g(\hat{h}, E) + p^r a(\hat{h}) - p^1\hat{h} - \tilde{w}E\right]$. In addition, a conventional animal feed producer manufactures animal feed with a production function $y(\bar{h})$ and profits $\pi^r = p^r y(\bar{h}) - p^1\bar{h}$.

The farmer produces either bioenergy crop or an alternative crop. Also, some parcels can be allocated to green set-aside. We assume that the alternative crop performs best in high land qualities and green set-aside in the lowest qualities. The return to green set-aside is constant, but profits from crop production depend on fertilizer application. Denoting the fertilizer intensity by l^i, the response function of crop *i* is $f(l^i, q)$ (with $f_{l^i} > 0$, $f_{l^i l^i} < 0$), where q refers to land quality. Profits per parcel from crop production are $\pi^i = \hat{p}^i f(l^i, q) - (c + b\eta)l^i$ where $\hat{p}^i = p^i - (\varphi + b\xi) - (\omega + b\psi)$ denotes the effective crop price, φ the grain drying cost and ω transportation cost. Parameters ξ and ψ denote the CO_2-eq emissions for grain drying and transportation (kg CO_2-eq / kg bioenergy crop), respectively. Furthermore, c is fertilizer input cost and parameter η represents the CO_2-eq emissions (kg CO_2-eq / kg nitrogen fertilizer) from fertilizer application. Hence, the profits from all agricultural production lines are defined by $PV = \int_0^1 \begin{bmatrix} \pi^{1*}(p^1, c, q)(1 - L^2 - L^3) + \\ \pi^{2*}(p^2, c, q)L^2 + \pi^3 L^3 \end{bmatrix} \delta(q)dq$ where $\delta(q)$ is a density function describing the distribution of land between different qualities. The model of heterogeneous land quality is further described in appendix 1.

B. Social optimum

The social planner maximizes social welfare defined as a sum of consumers' and producers' surpluses. Social welfare function represents the aggregate welfare of individuals in the society. The social welfare function is defined as a sum of relevant market actors' net profits and the climate impacts of ethanol production as defined previously. The bioenergy crop production is used by the two industries. Let z denote the (endogenous) share of production used in ethanol firm and (1-z) by the animal feed firm. Then $\hat{h} = z\int_0^1 \left(f^1(l^1, q)\right)\left(1 - L^2 - L^3\right)\delta(q)dq$ and $\overline{h} = (1-z)\int_0^1 \left(f^1(l^1, q)\right)\left(1 - L^2 - L^3\right)\delta(q)dq$ exhaust the production. The price of the alternative crop is exogenous in the problem. Definition of social welfare function is given in equation (2) in appendix 2.

The problem of the planner is to choose fertilizer intensity for both crops, the use of bioenergy crop in both firms, use of energy input and land allocation between the three land use forms. This results in six simultaneous equations which are presented in equations (2a)-(2f) in appendix 2.

Equation (2a) is conventional; energy input in used up to the point where the value of marginal product equals the effective input price comprising also the negative climate impacts. From (2b), bioenergy crop yield is allocated between the two industries so that the value of its marginal product is the same from both of them. Equation (2c) characterizes the input use intensity for bioenergy crop in any parcel. Fertilizer intensity is increased to the point where its marginal contribution to the value of marginal product of bioenergy crop in both industries is equal to the sum of its input cost (comprising also the cost of CO_2-eq emissions) and marginal climate benefits. The rest three are familiar from standard heterogeneous land quality models [3]. Equation (2d) defines input intensity for the alternative crop and (2e) and (2f) determine the land allocation between the three crops at two critical qualities, where bioenergy crop becomes as profitable as green set-aside (equation 2f) and the alternative crop becomes more profitable than bioenergy crop (equation 2e). Conventionally, private optimum can be solved by setting $b=0$.

III. EMPIRICAL APPLICATION AND RESULTS

We next apply the theoretical framework to Finnish agriculture. Barley (crop 1) is cultivated in whole country whereas the climate conditions restrict wheat (crop 2) cultivation to the southern and western parts of Finland. Following theoretical model we define and calibrate parametric functions to represent ethanol production and barley and wheat cultivation in Finland.

A. Parametric functions

A Cobb-Douglas production function is calibrated for barley ethanol production in Finland. Here we focus on the feedstock-to-ethanol conversion process in which following stages are taken into account: harvest of starchy parts of barley (straw/stalks used in combined heat and power production), feedstock conversion to sugar (including starch separation, milling, and conversion to sugars via enzyme application), process heat, sugar conversion to alcohol (including fermentation and distillation of alcohol), and co-products (distillers grains). Parameters of Cobb-Douglas production function has been calibrated on the basis of Finnish data on the use of barley and energy in the feedstock-to-ethanol conversion process.

Parametric profit function for ethanol production can now be defined as:

$$\pi^e = p^e A\hat{h}^\alpha E^\beta + p^r \phi\hat{h} - p^1\hat{h} - \tilde{w} \quad (3)$$

where ϕ is a technical coefficient expressing the relation between the use of barley in the ethanol production process and the production of animal feed. In the empirical analysis the demand for barley by the conventional animal feed manufacturer is assumed to be an exogenous parameter. Hence, the parametric definition of π^r is omitted.

We use Mitscherlich specification of nitrogen response function for barley (i = 1) and wheat (i = 2) defined as

$$f(l^i, q) = m^i(1 - \gamma^i e^{-\rho^i l^i}) \quad (4)$$

where m^i, γ^i and ρ^i are parameters and l^i is nitrogen fertilizer intensity. The parameters of Mitscherlich response function have been estimated on the basis of Finnish field trials by [4]. In order to calibrate the response function to actual yield levels corresponding to given nitrogen fertilizer use in Finland land quality is incorporated through parameter m^i which is assumed to be linear in land quality, i.e. $m^i = m_0^i + m_1^i q$. The model contains 19 one hectare field parcels of differential land productivity. Parametric profit function of crop i is thus defined as:

$$\pi^i = \hat{p}^i m^i(1 - \gamma^i e^{-\rho^i l^i}) - (c + b\eta)l^i - K^i + S^i \quad (5)$$

where K^i denotes the other per ha costs of cultivation than fertilizer (including seed, pesticide, fuel, labour etc.). S^i denotes crop area payments including CAP compensation payments and LFA payment. The return to green set-aside is constant and is defined by $\pi^3 = R - b\eta\bar{l}^3$, where $\bar{l}^3$ represents a constant per hectare fertilizer application in the establishment stage of green set-aside field. The profits from all agricultural production lines are defined by equation (6) in appendix 2.

Parameters of Mitscherlich nitrogen response function, crop and fertilizer prices, cultivation costs and support payments are provided in Appendix 3 Table 1.

In the social optimum, the social planner values the climate impacts of biofuel production. The valuation is incorporated into social welfare function through equation (1). Parametric version of the equation (1) is

$$b = b\left[\varepsilon\left(A\hat{h}^\alpha E^\beta\right) - \sum_{i=1}^{3} \mu^i L^i\right] \quad (7)$$

Combining equations (3), (6) and (7) results in a parametric form of social welfare function given in equation (8) in appendix 2. In equation (8), π^r represents the exogenous profits of conventional animal feed producer. Again, the private optimum can be solved by setting *b=0.*

B. Greenhouse gas emissions

Greenhouse gas emissions are modelled on the basis of life cycle assessment (LCA) estimates provided by [2], who analysed both bioenergy crops for combined heat and power (CHP) and biofuels (ethanol from barley and biodiesel from rape seed) for transportation. They estimated CO_2-equivalent emissions for the whole chain from the production of inputs to the final use of bioenergy and biofuels, including the manufacturing of inputs (such as fertilizer and pesticides), transportation of inputs and outputs, bioenergy crop production, conversion of feedstock to biofuels, and final consumption in transportation.

In this application, as presented in Figure 1, the following aspects are included in the agricultural phase: (i) CO_2-eq emissions related to the transportation of crops, (ii) CO_2-eq emissions related to the manufacturing, transportation and application of fertilizers, pesticides, and lime (iii) CO_2-eq emissions from soil and (iv) CO_2-eq emissions from tillage practices, such as ploughing, harrowing and planting as well as CO_2-eq emissions from harvest and grain drying. Moreover, following [2] we assume that barley straw is used in combined heat and power production, where it replaces peat.

With respect to the transportation of inputs and outputs the following assumptions are made. All transportation takes place with a EURO 3-class (capacity 60 tons) trailer truck (one-way 100% use of capacity). On the basis of this assumption the CO_2-eq emissions are 69.3 g/ton/km. The manufacture, transportation (200 km) and application (N_2O emissions from soil) of one ton of NPK (20-3-8) fertilizer produces 2.143 tons of CO_2-eq emissions, which translates into 10.715 kg CO_2-eq emissions per 1 kg of N fertilizer. The manufacture, transportation and application of one ton of pesticides cause 16.7 tons of CO_2-eq emissions and the corresponding figure for lime is 0.45 tons. The soil CO_2 emissions for wheat and barley are 1.43 t CO_2/ha/a, whereas green set-aside sequesters carbon by 0.05 t CO_2/ha/a.

As regards ethanol conversion process we take the following aspects into account: (i) CO_2-eq emissions from process energy and (ii) CO_2-eq emissions from storage and distribution of ethanol. Furthermore, following [2], we assume that distillers dried grain replaces imported soybean meal in feed production. As our focus is on climate policy, we consider ethanol to be carbon neutral. Thus, the end-use of ethanol does not increase the total amount of carbon in the atmosphere.

Total CO_2-eq emissions from the production and end-use of ethanol vary depending on the optimality conditions of barley cultivation. However, the ethanol production process and ethanol storage and distribution produce 35,000 g CO_2-eq / MJ. The CO_2-eq savings from straw replacing peat are 77,000 g CO_2-eq / MJ and the CO_2-eq savings from distiller's grains replacing imported soybean meal are 7,000 g CO_2-eq / MJ [2].

As a reference fuel we use conventional gasoline. According to [5], the CO_2-eq emissions from production of conventional gasoline are 11,727 g CO_2-eq / MJ. The end-use of gasoline produces 75,559 CO_2-eq / MJ [2]. The total CO_2-eq emissions from the production and end-use of conventional gasoline are thus 87,286 g CO_2-eq / MJ. The value for ε, which represents the difference in GHG-emissions between conventional gasoline and ethanol, is calculated from the above CO_2-eq emissions.

C. Empirical results

Empirical results of private and social optimum are presented in Table 1. Relative to the private optimum the price of barley is higher in the social optimum. Price increases from €200.29/tonne to €200.56/tone and this increase (0.135 %) results from taking into account the climate benefits associated with the production and use of ethanol from barley. The demand for barley is 13.3 % higher in the social optimum than in the private optimum.

Table 1 Private and social optimum for barley production in Finland

	Private optimum	Social optimum
BARLEY DEMAND		
Barley price (€/kg)	0.20029	0.20056
Ethanol production		
Ethanol production (t)	82 320	102 157
Animal feed production (from distillers' grains) (t)	127 408	161 444
Energy demand (GJ)	940 726	1 194 970
Barley demand (t)	283 129	358 765
Animal feed production of convention animal feed manufacturer		
Barley demand (t)	287 073	287 073
Total demand for barley	*570 202*	*645 838*
Agricultural production in Southern Finland		
Land allocation G:B:W*	6:2:11	15:3:1
Barley		
Fertilizer intensity (kg/ha)	121.6	118.1
Yield (kg/ha)	3 710	4 070
Land allocated to cultivation (ha)	18 539	34 897
Barley supply (t)	68 784	142 018
Wheat		
Fertilizer intensity (kg/ha)	164.5	154.2
Yield (kg/ha)	4 167	4 309
Land allocated to cultivation (ha)	118 867	10 905
Agricultural production in other areas		
Exogenous supply of barley (t)	503 880	503 880
Total barley supply	*572 664*	*645 898*

*G is for green set-aside, B barley and W wheat

Relative to the private optimum the social optimum favours green set aside due to its carbon sequestration benefits. Consequently land allocated to green set aside increases from 6/19 to 15/19. Social optimum favors barley cultivation as well and land allocated to barley cultivation increases slightly from 2/19 in the private optimum to 3/19 in the social optimum. Due to high fertilizer use intensity and related CO_2-eq emissions the land area devoted to wheat cultivation decreases remarkably in the social optimum. Overall only the most productive agricultural land is devoted to crop cultivation in the social optimum.

The socially optimal fertilizer use intensity for both crops is lower than the privately optimal (2.8 % for barley and 6.2 % for wheat). Despite of lower input use intensity the average yield increases for both crops because their cultivation shifts towards higher land productivities. The total supply of barley is 12.8 % higher in the social optimum than in the private one.

Table 2 CO_2-eq emissions in private and social optimum

	Private optimum	Social optimum
Fertilizer (t)		
Total fertilizer application	22 360	7 096
CO_2-eq emissions (t)		
Fertilizer (production and use)	239 588	76 031
Emissions from soil	193 465	58 010
Grain drying	37 014	12 401
Transportation (inputs and outputs)	6 638	2 224
Pesticides (production and use)	2 289	763
Tillage practices (ploughing, harrowing, lime, etc.)	40 816	26 025
Total CO_2-eq emissions	*519 810*	*175 452*

CO_2-eq emissions in the private and social optima are presented in table 2. The greatest source of CO_2-eq emissions in both private and social optimum is manufacturing and application of fertilizer. Due to reduced application intensity and decreased area of land allocated to the crops the total fertilizer use decreases by 68.3 % in the social optimum relative to private optimum. As a result the total CO_2-eq emissions from manufacturing and application of fertilizer decrease by 68.3 % as well. Emissions from soil decrease remarkably in the social optimum because land allocation shifts towards green set aside that sequesters carbon and thus its emissions from soil are negative. The total CO_2-eq emissions from soil are reduced by 70% in the social optimum relative to the private one. Tillage practices, including plowing, harrowing, planting and harvest is the third major contributor to the total CO_2-eq emissions in agriculture. Due to reduced land allocation to the crops the total CO_2-eq emissions from agricultural tillage practices decrease by 36.2 % in the social optimum relative to the private optimum. Overall the total CO_2-eq emissions are 66.2 % lower in the social optimum than in the private optimum.

IV. CONCLUDING REMARKS

The paper examines the social desirability of ethanol produced from agricultural crops. To endogenize the competition on land use, a Ricardian model of heterogeneous land quality was employed, where land is allocated to alternative crops on the basis of their relative profitability. The model comprises three land use types: bioenergy crop, conventional feed crop and green set-aside. The endogenous price effects and the effects on the GHG balance were explicitly taken into account. The theoretical framework was applied to ethanol produced from barley in Finland.

Our empirical results show that the socially optimal demand for barley is 13.3 % higher than demand obtained in the private optimum. Relative to the private optimum, the social optimum favours greatly green set aside and slightly barley relative to wheat cultivation. High fertilizer use intensity and related CO_2-eq emissions reduce remarkably the land area devoted to wheat cultivation in the social optimum.

As regards CO_2-eq emissions the greatest source of CO_2-eq emissions in both private and social optimum is manufacturing and application of fertilizer. Due to reduced fertilizer application intensity and decreased area of land allocated to the crops the total fertilizer use decreases in the social optimum and as a result the total CO_2-eq emissions from manufacturing and application of fertilizer decrease. Moreover, emissions from soil decrease remarkably in the social optimum because land allocation shifts towards green set aside that sequesters carbon and thus its emissions from soil are negative. Overall, the total CO_2-eq emissions are 66.2 % lower in the social than in the private optimum.

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Appendix 1 Agricultural land allocation and heterogeneous land productivity

A model of heterogeneous land quality is used in modelling the supply of barley. Let the total amount of land devoted to agriculture be *G*. The agricultural land is divided into parcels. It is assumed that the land quality within a parcel is uniform but the quality differs between parcels. The quality depends on physical, chemical and biological factors, such as soil textural class, organic content, and soil acidity. It is assumed that the land quality can be ranked according to a scalar measure *q*. The scalar varies between zero and one, $0 \le q \le 1$ so that zero is the minimal and one maximal land quality. The cumulative distribution of *q* can be written as $G(q)$ and the density is $\delta(q)$ which is assumed to be continuous and differentiable for analytical convenience:

$$G = \int_0^1 \delta(q)dq \qquad (1)$$

Let us assume that farmer can allocate the land between two different cereal crops, crop 1 and crop 2 and green set aside. It is further assumed that land with lowest quality is allocated to green set-aside and the share of it is denoted with L^3. It is assumed that crop 2 is more profitable than crop 1 at land of maximal quality and more responsive to changes in land quality. The respective shares of land allocated to crops are denoted by L^2 and L^1. The latter can be expressed as a function of L^2 and L^3 , $L^1 = (1 - L^2 - L^3)$. The profit function of crop cultivation for crops *i=1,2* is $\pi^i(p^i, c, q) = p^i f(l^i, q) - cl^i$ where p^i denotes the crop price, l^i the fertilizer intensity, $f(l^i, q)$ the fertilizer response function of crop *i* (derivatives $f_{l^i} > 0$, $f_{l^i l^i} < 0$), *c* fertilizer input cost and *q* land quality. It is assumed that the profit from green set-aside is constant with respect to land quality so that $\pi^3 = R$. The optimal fertilizer intensity $l^i * = l^i(p^i, c, q)$ for crops *i=1,2* is derived from the respective profit functions. The farmer first chooses optimal fertilizer intensity for both crops over all land qualities. Then each parcel is allocated to the crop which produces highest profits given land quality of the parcel. The total profits of farmer can be defined as

$$PV = \int_0^1 \begin{bmatrix} \pi^{1*}(p^1, c, q)(1 - L^k - L^2) \\ + \pi^{2*}(p^2, c, q)L^2 \\ + \pi^3 L^3 \end{bmatrix} \delta(q)dq \qquad (2)$$

The first order conditions of equation (2) are

$$\frac{\partial PV}{\partial L^3} = \pi^3 - \pi^{1*}(p^1, c, \bar{q}) = 0 \qquad (3)$$

$$\frac{\partial PV}{\partial L^2} = \pi^{2*}(p^2, c, q^*) - \pi^{1*}(p^1, c, q^*) = 0 \qquad (4)$$

The critical values of *q* can be solved from above equations and are expressed as $\bar{q} : \pi^3 = \pi^{1*}(p^1, c, \bar{q})$ and $q^* : \pi^{2*}(p^2, c, q^*) = \pi^{1*}(p^1, c, q^*)$. It is optimal for the farmer to allocate land to green set-aside when $0 \le q \le \bar{q}$. Crop 1 is the optimal choice when $\bar{q} \le q \le q^*$ $\bar{q} < q < q^*$ and crop 2 when $q^* \le q \le 1$. The shares of land for green set-aside, crop 1 and crop 2 are

$$L^3 = \int_0^{\bar{q}} \delta(q)dq = G(\bar{q}) \qquad (5)$$

$$L^1 = \int_{\bar{q}}^{q^*} \delta(q)dq = G(q^*) \qquad (6)$$

$$L^2 = \int_{q^*}^{1} \delta(q)dq = G(1) - G(q^*) - G(\bar{q}) \qquad (7)$$

Appendix 2 Additional equations

Social welfare function:

$$\begin{aligned} SW &= \left[p^e g\left(\hat{h},E\right)+p^r a\left(\hat{h}\right)-p^1\hat{h}-\tilde{w}E\right]+\left[p^r y\left(\bar{h}\right)-p^1\bar{h}\right] \\ &+\int_0^1\begin{bmatrix}\left(\hat{p}^1 f^1\left(l^1,q\right)-(c+b\eta)l^1\right)(1-L^2-L^3) \\ +\left(\hat{p}^2 f^2\left(l^2,q\right)-(c+b\eta)l^2\right)L^2+RL^3\end{bmatrix}\delta(q)dq+b\left[\varepsilon g\left(\hat{h},E\right)-\sum_{i=1}^{3}\mu^i L^i\right] \end{aligned} \tag{2}$$

First order conditions of equation (2):

$$SW_E = p^e g_E(\hat{h},E)-\tilde{w}+b_Q(\cdot)\varepsilon g_E(\hat{h},E)=0 \tag{2a}$$

$$SW_z = p^e g_{\hat{h}}\left(\hat{h},E\right)+p^r y_{\hat{h}}\left(\hat{h}\right)-p^r a_{\bar{h}}\left(\bar{h}\right)=0 \tag{2b}$$

$$\begin{aligned} SW_{l^1} &= \left[\left(p^e g_{\hat{h}}\left(\hat{h},E\right)+p^r a_{\hat{h}}\left(\hat{h}\right)\right)z+(1-z)p^r y_{\bar{h}}\left(\bar{h}\right)\right]f^1_{l^1}\left(l^i,q\right) \\ &-(c+b\eta)+b_Q g_{\hat{h}}(\cdot)f^1_{l^1}\left(l^i,q\right)=0 \end{aligned} \tag{2c}$$

$$SW_{l^2} = p^2 f^2_{l^2}(l^2,q)-(c+b\eta)=0 \tag{2d}$$

$$SW_{L^2} = \left(\pi^{2*}(p^2,c,q)-b\mu^2\right)-\left(\pi^{1*}(p^1,c,q)+b\mu^1\right)=0 \tag{2e}$$

$$SW_{L^3} = \left(\pi^3-b\mu^3\right)-\left(\pi^{1*}(p^1,c,q)+b\mu^1\right)=0 \tag{2f}$$

Profits from all agricultural production lines:

$$PV=\int_0^1\begin{bmatrix}\left(\hat{p}^1 m^1(1-\gamma^1 e^{-\rho^{1i}l^1})-(c+b\eta)l^1-K^1+S^1\right)\left(1-L^2-L^3\right)+ \\ \left(\hat{p}^2 m^2(1-\gamma^2 e^{-\rho^{2i}l^2})-(c+b\eta)l^2-K^2+S^2\right)L^2+\left(R-b\eta\bar{l}^3\right)L^3\end{bmatrix}\delta(q)dq \tag{6}$$

Parametric version of social welfare function:

$$\begin{aligned} SW &= \left[p^e A\hat{h}^\alpha E^\beta+p^r\phi\hat{h}-p^1\hat{h}-\tilde{w}\right]+\pi^r \\ &+\int_0^1\begin{bmatrix}\left(\hat{p}^1 m^1(1-\gamma^1 e^{-\rho^{1i}l^1})-(c+b\eta)l^1-K^1+S^1\right)\left(1-L^2-L^3\right)+ \\ \left(\hat{p}^2 m^2(1-\gamma^2 e^{-\rho^{2i}l^2})-(c+b\eta)l^2-K^2+S^2\right)L^2+\left(R-b\eta\bar{l}^3\right)L^3\end{bmatrix}\delta(q)dq \\ &+b\left[\varepsilon\left(A\hat{h}^\alpha E^\beta\right)-\sum_{i=1}^{3}\mu^i L^i\right] \end{aligned} \tag{8}$$

Appendix 3 Parameter values used in the empirical application

Parameter	Symbol	Value	
PRICES*			
Market price of ethanol	p^e	0.51615	€ / kg
Market price of wheat (in Finland)	p^2	0.21482	€ / kg
Price of animal feed	p^r	0.20164	€ / kg
Price of energy	$\tilde{w}$	0.00813	€ / MJ
Price of nitrogen fertilizer	c	1.32	€ / kg
Price of EU-ETS emission allowance	b	0.020	€ / kg CO_2
AREA PAYMENTS*	S^i		
CAP compensatory payments		249	€ / ha
LFA support		150	€ / ha
EXPENDITURE IN AGRICULTURE FOR OTHER VARIABLE INPUTS THAN FERTILIZER*	$\hat{K}$		
Machinery / cereals		329.00	€ / ha
Other variable costs / barley		185.00	€ / ha
Other variable costs / wheat		205.00	€ / ha
Other variable costs / green set aside		22.96	€ / ha
Harvesting / green set aside		96.58	€ /ha
Grain drying	φ	0.0145	€ / kg
Transportation	$\grave{\omega}$	0.0097	€ / kg
PARAMETERS			
Ethanol production function	α	0.73	
	β	0.18	
	A	1.35	
Technical coefficient of animal feed production	ϕ	0.45	
Mitscherlich nitrogen response function of barley	m^1	3813–4713	
	γ^1	0.828	
	ρ^1	0.0168	
Mitscherlich nitrogen response function of wheat	m^2	4136–5112	
	γ^2	0.7623	
	ρ^2	0.0104	
CLIMATE IMPACTS (CO_2-eq emissions)			
Nitrogen fertilizer	η	10.715	kg CO_2-eq / kg N
Soil + others / cereals	$\mu^{1,2}$	1701.356	kg CO_2-eq / ha
Soil + others / green set aside	μ^3	167.85	kg CO_2-eq / ha
Transportation	ψ	0.058811	kg CO_2-eq / kg
Grain drying	ξ	0.06561	kg CO_2-eq / kg
OTHER PARAMETERS*			
Animal feed demand for barley	D^r	287 073	t
Exogenous supply of barley (from other areas than Southern Finland)	θ	503 880	t
Total arable land in barley and wheat cultivation and as a green set aside (in Southern Finland)		207 200	ha

* All prices, costs, area payments and other parameters are from 2007.